IDENTIFICATION OF THE MATERIAL PARAMETERS OF A UNIDIRECTIONAL FIBER COMPOSITE USING A MICROMODEL

IDENTIFIKACIJA PARAMETROV MATERIALA ENOSMERNEGA KOMPOZITA Z UPORABO MIKROMODELTA

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Prejem rokopisa – received: 2011-10-20; sprejem za objavo – accepted for publication: 2012-02-14

The paper is focused on the identification of material parameters of the substituents of an unidirectional carbon-epoxy long-fiber-reinforced composite. Simple tensile tests using thin coupons with various fiber orientations were performed and force-displacement diagrams were obtained. A model of a unit cell is created in MSC.Marc. Fibers are considered to form a non-linear, elastic, transversely isotropic material and the matrix is considered to be an elasto-plastic isotropic material. The unit cell is loaded by a uniaxial stress up to the same level of loadings as the experimental samples. The sum of the squared differences of displacements between the numerically and experimentally obtained force-displacement diagrams is minimized within an identification process. The parameters of the linear relation between the Young’s modulus of fibers and strain in the fiber-axis direction, and three shape coefficients of the matrix work-hardening function are searched. The identification process is performed using the MSC.Marc, OptiSlang optimization software and Matlab.

Keywords: unidirectional fiber composite, non-linear behavior, optimization, identification, matrix work-hardening function, representative volume element, unit cell, micromodel

1 INTRODUCTION

Composite materials are widely used in all fields of industry such as aerospace, sport, automotive and transportation. Frequently used composites are based on a carbon-fibers and epoxy matrix for its high specific strength and stiffness. The knowledge of the material characteristics is crucial for the accuracy of the numerical models used in a designing process. The above type of composite shows a significant non-linear behavior. Therefore, complex non-linear material models must be used in order to achieve a good agreement with the experimental data even for the simple tensile tests. The modeling of large structures requires the use of macromodels, i.e., homogenized material models. The parameters of a macromodel can be assessed either by using a combination of a finite-element model with the mathematical optimization technique and experimental data or by using a micromodel of a unit-cell element, which is a periodically repeated volume fraction, with the knowledge of mechanical properties of all the constituents. A micromodel of the composite material can be advantageous for deeper analyses of the phenomena such as the influence of heterogeneities or microdamage mechanisms, etc.

2 EXPERIMENT

Tensile tests of the thin coupons made of unidirectional long-fiber carbon-epoxy composite SE84LV-HSC-450-400-35 were performed on the testing machine ZWICK/ROELL Z050. The coupons were cut by a water jet from one large plate.
The fiber direction forms the angles of 0°, 15°, 30°, 45°, 60°, 75° and 90° with the direction of the loading force (Figure 1). There were 10 specimens tested for each angle. Cracked specimens are shown in Figure 2. The specimens loaded along the fiber direction are fractured due to a fiber failure. All the specimens loaded at a different angle are fractured due to a matrix failure. The resulting force-displacement diagrams are shown in Figure 3.

2.1 Micromodel

A finite-element model (micromodel) of a periodically repeated volume (unitcell, Figure 4) of the unidirectional composite material was created in the finite-element system MSC.Marc. A perfect honeycomb distribution of the fibers and a fiber-volume ratio of 55% were assumed (Table 1).

Table 1: Geometry ratios of a unit cell

<table>
<thead>
<tr>
<th>Fiber radius</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short side length</td>
<td>1.28 $r$</td>
</tr>
<tr>
<td>Long side length</td>
<td>2.22 $r$</td>
</tr>
</tbody>
</table>

Assuming the uniaxial stress across the whole specimen, the behavior of the material can be simulated by loading the unit cell with the normal stress $\sigma$ corresponding to the external force $F$:

$$\sigma = \frac{F}{A}$$

where $A$ is a cross-section of the specimen.

The global coordinate system $(xyz)$ is given with the force direction $(x)$ and the direction perpendicular to the composite surface $(z)$. The local coordinate system $(123)$ is defined with the unit-cell edges, where the axis directions correspond to the fiber direction $(1)$ and the directions perpendicular to it (Figure 5).

The loading force is transformed to the local coordinate system using the transformation:

$$\begin{bmatrix}
  \sigma_1 \\
  \sigma_2 \\
  \tau_{12}
\end{bmatrix} =
\begin{bmatrix}
  \cos^2 \varphi & \sin^2 \varphi & 2 \sin \varphi \cos \varphi \\
  \sin^2 \varphi & \cos^2 \varphi & -2 \sin \varphi \cos \varphi \\
  -\sin \varphi \cos \varphi & \sin \varphi \cos \varphi & \cos^2 \varphi
\end{bmatrix}
\begin{bmatrix}
  \sigma \ \\
  0 \\
  0
\end{bmatrix}$$

where $\varphi$ is the angle of rotation between the local and the global coordinate systems.

The results from the finite-element analysis (strains) are transformed back to the global coordinate system using the transformation:

$$\begin{bmatrix}
  \sigma_1 \\
  \sigma_2 \\
  \tau_{12}
\end{bmatrix} =
\begin{bmatrix}
  \cos^2 \varphi & \sin^2 \varphi & 2 \sin \varphi \cos \varphi \\
  \sin^2 \varphi & \cos^2 \varphi & -2 \sin \varphi \cos \varphi \\
  -\sin \varphi \cos \varphi & \sin \varphi \cos \varphi & \cos^2 \varphi
\end{bmatrix}^{-1}
\begin{bmatrix}
  \sigma \ \\
  0 \\
  0
\end{bmatrix}$$

Figure 2: Cracked specimens with aluminum tabs
Slika 2: Razpokani vzorci z aluminijevo podlago

Figure 4: Three-dimensional mesh of a unit cell
Slika 4: Tridimenzionalna mreža enotne celice

Figure 3: Measured force-displacement diagrams (grey) for each fiber angle and the corresponding averaged values (black)
Slika 3: Izmerjeni diagrami sila – ponik (sivo) za vsak kot vlakna in ustrezen povprečen vrednosti (črno)

Figure 5: Rotated coordinate systems
Slika 5: Rotirani koordinatni sistem
\[
\begin{bmatrix}
\varepsilon_i \\
\varepsilon_j \\
\gamma_{ij}
\end{bmatrix} = \begin{bmatrix}
\cos^2 \varphi & \sin \varphi & -\sin \varphi \cos \varphi \\
\sin^2 \varphi & \cos^2 \varphi & \sin \varphi \cos \varphi \\
2 \sin \varphi \cos \varphi & -2 \sin \varphi \cos \varphi & \cos^2 \varphi - \sin^2 \varphi
\end{bmatrix} \begin{bmatrix}
\varepsilon_i \\
\varepsilon_j \\
\gamma_{ij}
\end{bmatrix}
\] (3)

The unit cell must also respect the periodical boundary conditions (shown schematically in Figure 6):
\[
\Delta u = u_b - u_A \\
\Delta v = v_b - v_A \\
\Delta w = w_b - w_A
\] (4)

where \(\Delta u\), \(\Delta v\) and \(\Delta w\) are the translation differences of a pair of opposing nodes in directions 1, 2 and 3, respectively. These differences must remain constant for all the pairs of the corresponding nodes on the opposite sides.

In MSC.Marc, the periodical boundary conditions were implemented using a combination of links defined in the Fortran subroutine and springs.

2.2 Material models

The experimental results from the tensile tests show a non-linear behavior of the composite even when loaded in the fiber direction (Figure 1). In order to capture this phenomenon a non-Hookean material model was considered for the fibers. The dependence of the longitudinal Young’s modulus of fibers on strain is:
\[
E_{11} (\varepsilon_{11}) = E_{11}^0 (1 + g \varepsilon_{11})
\] (5)

where \(g\) is the coefficient describing the measure of non-linearity and \(E_{11}^0\) is the initial Young’s modulus of fibers in the longitudinal direction.

The fiber is modeled as a transversely isotropic material. The standard material constants given by the manufacturer are in Table 2.

Table 2: Material parameters of the fiber given by the manufacturer
Tabela 2: Parametri materiala vlaken, dobljeni od proizvajalca

| \(E_{11}^0\) (GPa) | 230.00 |
| \(E_{22} = E_{33}\) (GPa) | 15.00 |
| \(G_{12} = G_{23} = G_{31}\) (GPa) | 50.00 |
| \(\nu_{12} \equiv \nu\) | 0.30 |
| \(\nu_{11}\) | 0.02 |
| \(V_f\) | 0.55 |

The work-hardening function which respects a non-linear behavior of the matrix was proposed in the following form:
\[
\sigma = \frac{E^m \varepsilon_p}{\left[1 + \left(\frac{E^m \varepsilon_p}{\sigma_0}\right)^n\right]^{\frac{1}{n}}}
\] (6)

where \(\varepsilon_p\) is an equivalent plastic deformation. The matrix material was modeled to be isotropic having a Poisson’s ratio of \(\nu^m = 0.3\) (given by the manufacturer).

2.3 Identification process

The average curve for the experimentally obtained force-displacement diagrams was calculated for each angle of the fiber direction. These averaged diagrams are considered as target curves for the further analysis. Hereafter, the unit cell was loaded with the stress components corresponding with the uniaxial loading of the samples (2). The unit cell is loaded up to the range corresponding to the maximum value of the loading force in the target curve. The displacement dependence on the axial force is obtained by transforming the unit-cell strains back to the global coordinate system (3).

The numerically obtained force-displacement diagrams are subsequently compared with the target force-displacement curves.

Table 3: Identified material parameters
Tabela 3: Identificirani parametri materiala

| \(g\) | (-) | 23.23 |
| \(E_{11}^0\) (GPa) | 189.93 |
| \(E^m\) (GPa) | 7.17 |
| \(\sigma_0\) (kPa) | 88.15 |
| \(n\) | (-) | 1.56 |
| \(\Delta \varphi\) (°) | -0.36 |

Figure 6: Equivalently deformed opposite boundaries of a heterogeneous unit cell
Slika 6: Ekvivalentna deformirana nasprotne meje heterogene enotide ceлице

Table 3: Identified material parameters
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| \(g\) | (-) | 23.23 |
| \(E_{11}^0\) (GPa) | 189.93 |
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| \(\sigma_0\) (kPa) | 88.15 |
| \(n\) | (-) | 1.56 |
| \(\Delta \varphi\) (°) | -0.36 |

Figure 7: Equivalent plastic-strain contours in the matrix for \(\varphi = 30°\) at the maximum load
Slika 7: Ekvivalenten kontur plastične deformacije matice za \(\varphi = 30°\) pri največji obremenitvi
An optimization process was performed using Matlab, the optimization system OptiSlang and MSC.Marc. The goal was to find the best combination of all material coefficients by minimizing the sum of the squared differences of the numerical and experimental displacements calculated as:

\[ e = \sum_{\phi} e_{\phi} = \sum_{\phi} \sum_{i=1}^{N} \left[ \frac{(\Delta l_{\text{EXP}} - \Delta l_{\text{FEA}})^2}{\Delta l_{\text{EXP}}} \right] \]  

(7)

Besides the material parameters from relations (5) and (6) an inaccuracy of the cutting of the samples was taken into account. This inaccuracy \( \Delta \phi \) was attributed to the angle \( \phi \) (Figure 5).

The identified material parameters are summarized in Table 3, an example of the plastic strain in the matrix is shown in Figure 7, and the resulting force-displacement diagrams are compared in Figure 8.

3 CONCLUSION

The tensile tests of the unidirectional fiber-reinforced carbon-epoxy composite coupons were performed for different angles of the fibers. A micromodel of the composite material was created. Parameters of the non-linear material models of both constituents (matrix and fibers) were identified in the optimization process. The parameters were identified by minimizing the error between numerically and experimentally obtained force-displacement diagrams. Moreover, a manufacturing inaccuracy during the specimen cutting was taken into account in the optimization.

Future research will be aimed at the effects of the material imperfections, such as fiber undulation or inclusions in the matrix, and the modeling of the material-failure processes.

Acknowledgement

The work has been supported by the projects GA P101/11/0288 and the European project NTIS – New Technologies for Information Society No. CZ.1.05/1.1.00/02.0090.

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